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Dry Weather Fears of Britain's Early 'Industrial' Canal Network

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Keywords: Drought, canals, history, reconstruction, water management, UK

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Introduction

Droughts are complex events that can be spatially extensive or regionally focused (Todd et al. 2013). Large scale droughts are a recurrent feature of European climate (Spinoni et al., 2015), with notable British droughts in 1975-76 (Rodda and Marsh 2011; Zaidman et al. 2002), 1995-96 and 2003 (Fink et al. 2004), and recent droughts such as 2010-12 (Lennard et al. 2014) highlighting the Britain's vulnerability. However, these droughts are not unique or exceptional, with a long history of droughts impacting on European and British climatic history (Spraggs et al. 2015). The wide scale megadrought of 1540 is well documented across Europe (Wetter et al. 2014), but caused limited impact in Britain, whilst the 'long drought' (1880-1910) as documented by Marsh et al. (2007) highlights that droughts may be a single event, or a series of events in close succession. Whilst much of the analysis of past droughts has focused on drought reconstruction (Brázdil et al. 2018; 2013; 2008), increasingly past droughts are being viewed relative to other drought indicators, for example water resource management (Lennard et al., 2015, 2014) and hydrological drought (Jones and Lister 1998).

Definitions of droughts are frequently characterised within five inter-related categories: meteorological, hydrological, agricultural and socio-economic drought (Wilhite and Glantz 1985), with groundwater drought added by Mishra and Singh (2010). Droughts usually begin following a prolonged period of widespread moisture deficiency (Palmer 1965) and propagate through the hydrological cycle (Lanen 2006), exhibiting differing spatial and temporal characteristics depending on a variety of factors. Droughts are often defined as dry periods relative to climatic norms and occur even in climates where normal conditions are relatively wet (Namias 1981). They are not only geophysical events, but are also socially constructed, with societal structures effecting impacts and perceptions of drought (Endfield et al. 2004; Olivier-Smith and Hoffman 1999). Recent work has highlighted the importance of people in understanding contemporary drought (Van Loon et al. 2016a; 2016b), however this can also be extended into the past. Drought in Britain before the industrial revolution caused fires, disease, mortality (human and animal) and crop failures (Stone 2014 p. 437), but as industrialisation took hold, the impacts became more connected to the availability and quality of water for industry, transport and drinking.

The first large-scale water supply systems in Britain provided water not for domestic or industrial use, but for the canal network, the arteries of the industrial revolution. Analysis of the impact of dry weather on water supply networks has predominantly focussed on the supply of potable water in urban areas (Lieshout 2016; Taylor et al. 2009; Waddington 2017). Little attention has been paid to the role of canals and the significance of the development and expansion of the early canal network, particularly the role of reservoirs. The systems supplying canals generally predate large-scale potable water supplies, which were in their infancy when the water supply systems for canals were established. During the eighteenth and early nineteenth centuries, water for towns was rarely transported more than a few kilometres (Lieshout 2016; Porter 1978; Taylor et al. 2009). Taps inside houses were a luxury and water was seldom stored in sufficient quantities to provide a supply during droughts (Hassan 1985). Canals were the first water supply system to regularly transport water long distances in Britain, and to establish large scale water storage systems as a result of drought and competition for water. The builders of late eighteenth century canals negotiated rights to water, which later informed how commercial water companies managed their supplies. By responding to water shortages, they laid the groundwork for modern water supply resilience.

This paper explores the dry weather fears of Britain's early industrial canal network through the impact of droughts on canal operation in the late eighteenth century. It presents a previously unpublished long instrumental precipitation reconstruction for Chatsworth in Derbyshire and demonstrates the impact of droughts on the development of canal infrastructure, particularly the nearby Trent and Mersey Canal. It argues that the development of the canal network, which was driven in part by responses to drought, was an important phase in the development of water supply systems in the Britain, which has previously been overlooked.

In exploring how the early canal network developed and its vulnerability to droughts, this paper also contributes to the growing literature exploring how past experiences can, and continue to, shape our understanding of contemporary climate (Adamson, 2015; Adamson et al. 2018; Mitchell 2011;

Westermann and Rohr, 2015) and hazard adaptation and resilience (Jones et al. 2012; Sangster et al. 2018).

The development of canals in the eighteenth and nineteenth centuries

Movement and transport of water for irrigation and communities has been a feature of the water landscape since early settlements (Middle East c. 5000 BC), but these systems often remained relatively simple in structure and scale (Bazza 2007). In Britain, transporting heavy and bulky goods by water has been undertaken for many centuries (Blair 2014; Gardiner 2017). The early industrial canal network expanded and improved on an earlier system of natural and engineered navigable rivers, supplemented by some artificial channels (Bond 2014). These river navigations were subject to seasonal variation in flow and liable to movement of sediments during periods of high flow, which could be easily render the channel unnavigable (Satchell 2017). The modification of river channels to allow for easier navigation only provided short term improvements; widening, deepening or reducing sinuosity often increased the water velocity and concurrently increased erosion rates and downstream silting (Rhodes 2014). As Thomas Telford (1757-1834), the notable civil engineer remarked in 1800, 'artificial canals have been formed in many parts of the country, and the navigation of many of the other rivers in this island have been greatly improved; yet still the navigation of the river Severn has been suffered to remain in its natural and imperfect state; not one obstacle has been removed, nor has one improvement been yet introduced.' One of the causes of the 'imperfect state of the navigation' was 'the deficiency of water in drought, and from the superabundance of it during rainy seasons' (Plymley 1803, p. 286). These navigable rivers were unpredictable and uncontrollable, the canals of the early industrial age attempted to improve upon them by taming and redirecting nature. Water was captured and controlled in slow moving and relatively straight channels of predetermined dimensions, thereby significantly reducing problems caused by sediment movement. However, these characteristics could themselves present problems of sedimentation where water sources introduced sediments to the canal network.

In the second-half of the eighteenth century, many long-distance canals were constructed. Travel by water was susceptible to extreme weather, with major disruptions caused by dry, wet and cold weather recorded (Freeman 1980; Satchell 2017). The earliest industrial canals, like the river navigations before them, mostly sourced their water from streams and rivers along their length, although sometimes supplemented with water drained or pumped from mines (Boughey and Hadfield 1994, p. 47; Hadfield 1969, p. 20). As a result, the supply of water to these canals was sometimes no more reliable than the supply of water to river navigations, with canals frequently suffering from water shortages and freezing (Freeman 1980). The early canal builders did not greatly innovate when establishing the water supplies to their canals; consequently, their canals were often vulnerable to water shortages. As the number of canals increased, the amount of stream and river water available to new enterprises decreased. Acts of Parliament concerning canals became increasingly prescriptive about the use of surface water. Clauses giving rights to take flood or rain water or to compel mine owners to raise water pumped out of their mines to a level at which it could be discharged into the canal, were widely adopted. While the Duke of Bridgewater's Canal (the first industrial canal, opened 1761) Acts (32 George II, c. 2, 33 George II, c. 2, 2 George III, c. 11) contained only a few sentences about water supply, by the 1790s, multiple paragraphs described the rights and the restrictions on using water (see for example the Rochdale Canal, 34 Geo III c. 78 or Newcastle(-under-Lyme) Canal, 35 George III, c. 87).

The long-distance canals of the industrial age faced additional water supply challenges compared to river navigations, as they crossed watersheds, where water was naturally in short supply. Some, relatively small, reservoirs were built at the same time as the early canals, to regulate the supply of water to these difficult to supply summit sections. Although bigger than the average mill pond, these reservoirs operated in a similar way, allowing canal companies to (in the words of the standard clause of the earliest canal acts regarding reservoirs) 'more conveniently' supply their canals and locks with water. These reservoirs regulated the flow on a daily and weekly scale, but did not store sufficient water for use during longer periods of dry weather.

Canals, therefore, as arguably the largest water users in early industrial Britain and faced some of the most severe drought impacts in this period. Much can be learnt about canals and the effects of extreme weather in the late eighteenth and early nineteenth centuries by examining the archival material relating to canals alongside historical weather data. Many of the canal company archives are located within local, regional and the National Archives at Kew (TNA). An initial archival search for documents relating to water shortages on canals was undertaken at the Staffordshire Record Office (SRO), which resulted in the discovery of a substantial amount of material in the Sutherland Estate Collection, including correspondence with the Clerk of the Trent and Mersey Canal Company (SRO D593/L/1/14) and Acts of Parliament and related material (SRO D593/V/3/29). Other relevant material at the SRO included letters sent by Samuel Barnett and Company (tin manufacturers in Kings Bromley) between 1796 and 1803 (SRO 6702/1), and the Staffordshire Quarter Sessions records (SRO Q/SB 1810 T/466). The company archive of the Trent and Mersey Canal Company does not survive intact, though some records, which for the eighteenth century are mainly financial, are stored at the TNA (RAIL 878). The archive of the neighbouring Staffordshire and Worcestershire Canal Company, however, survives, split between the SRO and the TNA. The minutes of the half-yearly meetings of the Staffordshire and Worcester Canal Company 1766-1845 were read (SRO D3186/1/1/1) alongside surviving committee order books 1766-1785 and 1803-1804 (TNA RAIL 871/1, RAIL 871/2). Letters written between 1797-1801, preserved in the letter book of civil engineer John Rennie (1761-1821) were another key archival source (ICE REN/RB/02). The TEMPEST database was searched for corroboratory archival evidence (Veale et al. 2017). In order to complement the rainfall series from Chatsworth, material selected for this paper relates mostly to the Trent and Mersey canal, although impacts were felt across the country and canals elsewhere faced similar problems.

The Trent and Mersey canal was authorised by Act of Parliament in 1766 (6 Geo III c.97) and construction finished in 1777. Its summit level, which was the most difficult to supply with water, is on the border between the counties of Cheshire and Staffordshire. This summit level is ~34 kilometres from Chatsworth House, where, as this paper will detail, a long instrumental precipitation series has been reconstructed, with monthly homogenized rainfall series from 1777 (when the Trent and Mersey canal fully opened) to the present day. The reconstructed precipitation series for Chatsworth provides a new long series, which is likely to be representative of the rainfall at summit of the Trent and

Mersey canal, since comparison with non-instrumental records from Trentham, near Stoke-on-Trent, several kilometres the other side of the summit of the canal show similar precipitation patterns.

Chatsworth House precipitation reconstruction

Chatsworth House, located ~25km southwest of Sheffield (Figure 1), is the ancestral home of the Duke and Duchess of Devonshire and has been owned by the Cavendish family since the purchase of Chatsworth Manor in AD 1549.

Weather data was recorded at Chatsworth from 1760 to 1813 and from 1860 to the present day. The early Chatsworth series 1760-1777 consists of annual precipitation totals. It is likely a higher resolution series (daily) existed for this period, but can no longer be found, though some monthly values were published by Farley in the *General View of the Agriculture and Minerals of Derbyshire* (1811). The monthly precipitation totals for Chatsworth 1777-1793 (Supporting Online Material Figure 1) are reported by the *Memoirs and Proceedings* of the Literary and Philosophical Society of Manchester (Garnett 1796). Following this, only annual totals are available for the period 1793-1800, as reported by George Cavendish, however monthly data for Manchester allows the Chatsworth annual series to be scaled to provide monthly data. Monthly values are again available from 1800-1810. The original record appears to end in 1810, at the same time as the death of Henry Cavendish, though annual totals continue to be reported in the Meteorological Office accounts until 1813. A gap then exists until 1860 when records recommence, with data supplied to British Rainfall, with the records now retained in the archives of the Meteorological Office (Exeter), with the series running through to the present. The Chatsworth House series can be reconstructed by using published and unpublished data, supplemented with precipitation records from Welbeck Abbey (~30km away) for which monthly meteorological observations during the period 1806-1878 exist. This permits the reconstruction of a homogenized composite monthly rainfall series (Table 1), notable in comparison to other coeval reconstructions, as it represents a rural area (Derbyshire) in central England and one of the longest rainfall series in Britain; from 1777-present day and with an annual series from 1760-present.

Farley (1811), a geologist and surveyor argued that weather registers, such as that kept at Chatsworth would ‘in time prove of the greatest importance, as the foundation of a Science of Meteorology’ (p.103). The value of such series are increasingly being recognized in helping understand long-term climate variability, but also provide a better understanding of extreme event frequency (Sangster et al. 2018). The rain-gauge at Chatsworth House was monitored by the gardener, who maintained meticulous notes on the weather conditions, with abstracts published in scientific accounts of the period, including, the *Memoirs and Proceedings* of the Manchester Literary and Philosophical Society (Supporting Online Material Figure 1). As with the promotion of new farming practices at the time, improvements in estate management and the construction of farm buildings, the recording of weather data were often pioneered at large estates like Chatsworth (Jankovic 2000). The recording of early instrumental meteorological data, such as, barometric pressure, temperature, rainfall, wind direction and strength provides valuable quantitative data as to the nature of the weather and climate in the past and can be used to help recover local climate histories (Strauss and Orlove 2003).

Precipitation series reconstruction, homogenisation and homogeneity testing

A number of components of precipitation record are used in reconstructing the Chatsworth House series, 1760 to present. Three primary series are used in the composite reconstruction, the series of monthly and annual data at Chatsworth House (1760-1810), the series from Welbeck Abbey (1806-1878) constructed by Craddock (unpublished) and the series from Chatsworth House that is continued to present (1860-). The greatest uncertainties are likely to be with the early Chatsworth series, as meteorological instruments were not consistently used nor designed. Consistency in siting of meteorological instruments closely relates to the development of the British Rainfall organisation (1860-) in Britain and the pioneering work of G.J. Symons (Pedgley 2002), as such early instruments were often attached to walls or in poorly selected locations, resulting in erroneous data.

To extend the earliest part of the record (part A; 1760-1810), linear regression analysis was performed using annual data from Chatsworth House and monthly and annual data from Manchester (~50km away) for the overlapping period 1786–1800. A good relationship exists between annual precipitation

(R^2=0.7) and monthly (R^2=0.54) totals, with monthly data adjusted to ensure comparability to the earlier Chatsworth House series. The period 1810-1860 was infilled at Chatsworth using monthly data for Welbeck Abbey, the regression equation (using overlapping data 1860-1878; R^2=0.59) was used to adjust data from Welbeck Abbey to ensure comparability with data observed at Chatsworth House and to construct the second part (B) of the homogenous record: 1810-1860. Existing transcribed data for Chatsworth House (1860-) was downloaded from the British Atmospheric Data Centre (BADC; Met Office 2018) and checked against the original records from Chatsworth House, with gaps in the transcribed series infilled from the original records. The two section A and B are then adjusted to the Chatsworth House series (1860-), part C.

Visual inspection of the composite series (Figure 2) illustrates that discontinuities exist within the early record. Annual mean rainfall for 33-year periods in each of the primary series Chatsworth 1777-1810: 700mm; Welbeck Abby 1811-1843: 784mm and Chatsworth 1909-1942:821mm illustrates that the early period is likely to have suffered from ‘under-catch’, a common challenge in old records (e.g. Groisman et al. 1991). The late 1870-1890s are recorded in several British stations as being particularly wet (1875-1894: 961mm annual average), this is evident within the Chatsworth series (1882 is the wettest year in the full series, 1418mm), therefore this period was not used for comparative purposes when assessing 33-year periods, with the period 1909-1942 selected as more representative, the average rainfall over the period 1860-2013 is 845mm. Annual average rainfall totals for three parts of the record: A, B and C, were calculated along with annual percentage differences. Comparison of parts of the record showed that the average percentage difference between section A with section C was 17.2%, and section B and C was 7.3% (Figure 2); rainfall values comprising sections A and B were increased respectively to correct for these inhomogeneities (Figure 2).

The homogeneity of the constructed rainfall series for Chatsworth was statistically assessed by cross-comparing with other independent long rainfall records, which are considered homogenous from a number of sites within a similar precipitation region (northwest England), and from others distributed across England that have a long series. Whilst there is good general correlation between Chatsworth with Manchester (r=0.61, p=<0.001) and Pode Hole (Spalding, ~105km away) (r=0.668, p=<0.001) respectively for the period 1786-2015, there are notable years of difference in total accumulated precipitation. For example, in 1839, Manchester recorded 89.8% of average rainfall, Chatsworth 133%, whilst the station at Mansfield (~28km away) recording 135% of average precipitation. A double mass curve test (Craddock, 1979) was undertaken, directly comparing cumulative rainfall totals between a sample station, for instance Chatsworth and reference station(s), like Manchester and Pode Hole (Spalding) to assess relative homogeneity. Gradient changes in the curve indicates discontinuity in one of the two series, which may arise from natural or non-natural causes (e.g. urbanisation of instrumentation sites). Comparison to the Manchester (1786-2015) and Pode Hole (Spalding, 1726- but for comparison in this study 1786-2015) series are made, but few other regional long series exist (other series potentially are Liverpool and Oxford, but these may be less representative as Liverpool has a local coastal influence to its climate and Oxford is further away ~165km) and Manchester and Pode Hole (Spalding) are the longest series that have been quality controlled and checked for comparable timescales. The series for Pode Hole (Spalding) was reassessed and quality controlled by Todd et al. (2013), the Manchester series created by Gordon Manley (1972) and subsequently updated and reassessed (Macdonald unpublished). Double mass curve testing has been widely applied to determine the relative homogeneity of climate time series, but this approach does not provide information on discontinuity timing, change of magnitude, or attribution of the break to a particular series (Camuffo et al. 2013; Craddock 1979). Therefore, standard normal homogeneity testing (SNHT) developed by (Alexandersson 1986) is used to indicate the timing and magnitude of potential inhomogeneities in the series. Annual rainfall cumulative curves are plotted for the three stations with breaks of slope denoted by the grey bars (Figure 3a, b, c).These breaks are statistically significant breakpoints, determined (Tv >7.75; n=25; significance level 95%) by difference calculations for two contiguous 25-year windows moved at annual steps through the data series and using the mean difference in precipitation between the two stations (Figure 3d,e,f). The breakpoints exceeding the Tv >7.75 threshold in the Chatsworth House – Manchester analysis, in 1850; 1875; 1903; 1916 and 1943 and are not replicated within the Pode Hole (Spalding) – Chatsworth House analysis, though comparison of Pode Hole (Spalding) – Manchester does identify the same period (1875), suggesting a inhomogeneity may exist within the Manchester series. Q*i* series (the standardized difference between the two rainfall series) show good alignment (Figure 3g,h,i). In analysing long reconstructed series, there is often greater distance between comparison sites than in analysis of contemporary climatic datasets, though the additional record length provided by reconstructed series is valuable in examining long-term variability and whether changes may be anthropogenic or climatic in origin. The peak in precipitation identified at Chatsworth (1875-1886; Figure 2) is replicated at other sites with instrumental series, though not as pronounced; 1875 to 1886 is noted elsewhere to have been a particularly wet period in England with several large floods (Brooks and Glasspoole 1928; Macdonald and Sangster 2017; Marsh et al. 2005). There are no known evidence of physical cases for breakpoints in the years identified (Figure 3). Though little information is retained on changes in instrument at the station, fortunately for Chatsworth a discussion of the early gauges is provided in the notebooks, though not of its exact siting, but this does not contribute to explaining the break points identified.

The reconstructed composite precipitation series has then been analysed using the standardised precipitation index (SPI), developed by (Mckee et al. 1993), which uses rainfall data to quantify precipitation excess or deficit, typically over 1–24 months, were negative values indicate drier conditions and positive values wetter conditions compared to the norm. The SPI is preferential to many other drought indices over long timescales as it has limited data input requirements (Lennard et al. 2015), the SPI-6 (standardised precipitation index – using a six month series) and SPI-12 (standardised precipitation index – twelve month) derived from the homogenised precipitation series for Chatsworth House are presented in Figure 4. The wet phase in the 1870-1880s is notable, with extreme droughts noted with an SPI <-2 (McKee et al. 1993). The well documented drought of 1975-76 is evident, but so are several earlier droughts, which are of comparable or greater severity.

Drought and Canals

During the 1770-90s the British canal networks were in their infancy, lacking large reservoirs to compensate for dry weather. As a result of insufficient water supplies, canals lacked resilience. Dry weather often resulted in water shortages; a series of notable droughts arising during this early period of canal development with impacts on both the canals, but also more widely in England. In both 6 and 12 month SPI series for Chatsworth, the year 1785 stands out as a particularly severe drought, with peak severity occurring in May 1785 (-4.39) and July 1785 (-3.72) in the 6 and 12 month SPIs respectively. Corroboratory archival evidence supports this, with several accounts in the TEMPEST database (Veale et al. 2017) documenting the impacts of the severe drought of 1785 regionally and nationally. Estate correspondence from Husbands Bosworth in Leicestershire (~90km to the south), talks of the 'calamitous season', with land-agents (estate managers) writing in July 1785 noting that 'by reason of an extraordinary drought, the graziers are in the greatest distress' (LLRRO DG39/708) and also commenting on a fire, which spread rapidly because of the dryness, requiring a house to be pulled down to halt its progress (LLRRO DG39/708). Fast developing early modern towns, with closely spaced wooden buildings, were vulnerable to fire, particularly during dry weather (Morgan 2016). Pasturage, and winter hay, for grazing animals is quick to suffer during a drought, and reports of dry, brown grass appear frequently in reports of dry weather, of both aesthetic and agricultural concern. Others also noted impacts on mills from the drying of watercourses, and moorland fires during the drought of 1785 (Garnier et al. 2015). In considering the archival accounts from 1785, the drought can be seen to have had meteorological, hydrological, agricultural and socio-economic impacts on the local communities.

Maintaining constant canal water supplies in the latter part of the eighteenth century appears to have been problematic, with 1785 a particularly difficult year. In 1797 the Trent and Mersey Canal Company (when proposing a new reservoir) reported to a parliamentary committee that they faced particularly severe water shortages in the years 1785, 1788, 1789, and 1791, 1792, 1793, 1794, 1795, and 1796 (SRO D593/V/3/29). The water shortages in 1785, 1788 and 1789 may be directly related to droughts, reflecting a possible national drought rich phase; Todd et al. (2013) note the period 1783-1791 at Oxford as one of the most severe drought periods (1767-2011). The water shortages in 1791-6 are likely to be the result of a combination of dry weather and increased canal traffic. The onset of the 1788-9 drought occurred in November 1788, as evidenced in both SPI-6 and SPI-12, with termination at the end of May 1789 (SPI-6) and mid-June 1789 (SPI-12). Whilst the summer of 1788 was not remarkably dry, March, April and May had between 54% and 84% of mean rainfall, which may have been sufficient to cause problems for the canals. The final months of 1788 were dry, with only 18 mm of rain in November and 3 mm of rain in December, and overall the year saw only 70% of mean annual rainfall at Chatsworth. The summer months of June and July were actually wet in 1789, both having more than double the mean rainfall, however, without the capability to actively manage the water using reservoirs, this rainfall will have been little use to the canal company.

It appears there is no simple relationship between rainfall and water shortages on canals. This is unsurprising, since water for canals was acquired from a combination of river and ground water sources (including mine discharges), therefore a delayed response to rainfall deficit is to be expected, as is regional variation (Lennard et al. 2014). Human factors also have a major influence; such as canal traffic and competition with other water users, which could greatly affect amounts of water available during dry weather. The droughts of the 1780s, however, do seem to have had an impact on the canal network, and should therefore be considered as factors in changing policies towards water use in the following years.

Impacts of insufficient water supplies on canals

The drought of 1785, and less severe droughts in 1788-9 and in the 1790s, had a notable impact on the canals, because the water supply did not keep pace with water demand. Rarely were these shortages so severe that the canals became completely unnavigable to all traffic, but they often meant that boats were forced to navigate with significantly decreased loads (Boughey and Hadfield 1994; Freeman 1980). In 1797, a witness to the Lord's Committee on the Bill for the Leek Branch of the Caldon Canal and Rudyard Reservoir stated that boats sometimes carried less than half a load in very dry weather, and often only three quarters of the normal load, and even following these reductions, could still be obliged to offload further goods on the canal banks to pass particularly shallow sections (SRO D593/V/3/29). Canal companies and boat operators faced both a reduction in income and higher costs when boats navigated with smaller loads.

The immediate financial cost was not the only problem created by water shortages. Repeatedly reducing loads risked damage to goods and extended delivery times. Significant transport delays might be faced by companies using canals to transport their raw materials and products, as a result of a build-up of goods in warehouses awaiting space on a boat for their onward journey. Delays at warehouses due to frosts, floods or water shortages feature several times in the letters of Samuel Barnett and Company (SRO 6702/1), with occasions where goods were left waiting more than a month before the backlog was cleared and they could be put aboard a boat for transportation. The impression given by these letters is that canal transport was unreliable and unpredictable in part because of the vulnerability of the canal system to extreme weather.

In addition to direct impacts on the canal companies and those directly involved in trading using the canal network, there could be wider and unexpected implications of water shortages for the canal network. There were some materials, for example, paving-stones and other road building materials transported by canal boat that in times of good water supply paid significantly reduced tolls, but which could not be carried on the canal during water shortages. Hence in 1810 the inhabitants of Newcastle-under-Lyme could not repair their roads because the paving-stones were delayed due to water shortages on the Caldon Canal (SRO Q/SB 1810 T/466). The impact of dry weather on canals might have far reaching consequences, affecting everyday activities unconnected to the canal.

Competition and Conflict

Water shortages on canals have previously been attributed to a combination of increasing competition for water and increasing traffic (Boughey and Hadfield 1994, p. 47). Undoubtedly, other water supply issues compounded the problems caused by dry weather, in particular competition between water users. Both water shortages and water supply innovation may have been driven by increasing competition for water. The canal companies were required by Act of Parliament to pay compensation for any water that they used to the deficit of other water users. Determining the impact of canals on the surrounding area was a time-consuming and expensive process, requiring agents of the canal companies, canal commissioners and landowners to enter into lengthy discussions.

Rivers suitable for operating mills would often have many mills and weirs along their length (Downward and Skinner 2005), and any mill negatively impacted by water being redirected for the canal would be entitled to compensation. In 1796, an agent of the Trent and Mersey Canal company described the payments of compensation as ‘bothersome’, and ‘growing daily with the increase of trade and population’ (SRO D593/L/1/14/2). The Trent and Mersey Canal Company purchased at least one mill that was previously using the water that they needed to take to supply the canal. The Staffordshire and Worcestershire canal similarly leased water mills in lieu of paying compensation (SRO D3186/1/1/1). These, however, were not long-term solutions, and only effective at a local level. To avoid competing with other water users, the canal companies were obliged to look to alternative water sources.

The economic pressure of compensating other users for loss or reduction of their water supply resulted in many canal companies investing in technologies and management techniques. Technical advances made it possible to increase the size or number of reservoirs and investing in machinery to pump water to where it was needed became a viable option and an obvious solution for many companies (Boughey and Hadfield 1994), but looking beyond rivers and streams for water supplies also became necessary.

Water shortages were almost exclusively a summer phenomenon, often coinciding with periods of dry weather. To describe them as simply an effect of growing competition for water, misses a more complex story concerning the interaction between weather and water demand. It does not take into account the impossibility of maintaining constant water supplies during periods of low flow, without the use of storage reservoirs.

Innovation

New infrastructure was needed to allow canal companies to make use of rain and flood water during drier times of year. Earlier small reservoirs were insufficient to hold excess water during times of heavy rainfall, and water frequently flowed over the top of their dams (SRO D593/V/3/29). On the

Trent and Mersey Canal, nearly all the reported water shortages effected the Caldon Canal, a branch which joins the main canal near its summit (Hadfield 1969; Lindsay 1979, p. 64). Although navigable and an important link to sources of limestone, a major function of the Caldon Canal was to bring water from the three main reservoirs at Knypersley, Stanley and Bagnall (Binnie 1987, p. 112; SRO D593/V/3/29). The Caldon Canal's two roles as feeder and as navigable canal were not always compatible, and the water in the Caldon Canal itself drawn down into the main canal during periods of dry weather.

With increasing competition from other water users, the Trent and Mersey Company investigated new sources of water, and in 1793, without finding any significant source of water from nearby streams or springs, they started to plan a new reservoir to catch flood and rain water, which would be much larger than any that had been built in Britain before.

In 1797 they obtained an Act of Parliament and built Rudyard Reservoir, in a valley in the North Staffordshire. With a surface area of 65 hectares (0.65km^2), Rudyard is more comparable to later drinking water reservoirs than its canal predecessors (which rarely exceeded 10 hectares). When the bill for its construction was taken to parliament, the only precedent was a reservoir 'not quite so large, but pretty nearly so… belonging to the Rochdale Canal' (D593/V/3/29). It appears that the planners of Rudyard were unaware of the Lac de Saint-Ferréol which had supplied the Canal du Midi in France since 1672 (Mukerji 2009). In this light, Rudyard reservoir was the legislative test case for later reservoirs. It was designed to be about 2 miles in length (3 kilometres), with dam heights quoted as between 42 foot (12.8 metres) and 30 foot (9 metres) high, with an innovative dam to match its innovative size, designed by canal engineer John Rennie (Binnie 1987).

The new scheme faced considerable opposition; many of the arguments against the reservoir focused on the size of the proposed reservoir, and suspicions of a hidden motive behind the construction. Opponents to the scheme suggested that Rudyard was too big to be filled with rainwater alone and therefore that the Trent and Mersey Company was planning to divert river water into it after construction (TNA RAIL 1019/15/41). Without precedent, Rudyard Reservoir represented the beginning of a new phase of water engineering and used water in a way and on a scale previously unseen in Britain.

Long-term Impacts

This period can also be seen as an important step in the establishing of rights over water; Rudyard reservoir is important as the legislative test case which paved the way for building large capacity reservoirs, which are an essential component of the modern provision of reliable and resilient modern domestic water supplies. However, Rudyard also had other, more direct long-term impacts on reservoir building, since it has been suggested that the innovative dam was used as a prototype for at least two other major dams (Binnie 1987). These include later canal reservoirs, such as the enlargement of Knypersley, another of the Trent and Mersey Company's reservoirs, but also Glencorse Reservoir (Binnie 1987). Glencorse was built in the early nineteenth century to supplement Edinburgh's public water supply and provides a direct link between the early large capacity reservoirs and later potable water reservoirs. Rudyard was also the first large compensation reservoir, supplying a gauged amount of water equal to the flow of the River Churnet in normal conditions at all times of year (ICE REN/RB/02/001). The construction of Rudyard Reservoir, therefore, could be seen as a technological milestone.

A number of former canal reservoirs were repurposed as potable water reservoirs in the twentieth century, providing a further link between canal reservoirs and the modern water supply. Most small and some large reservoirs, such as Rudyard and Chasewater, were retained by the canal companies despite the decline in commercial canal use. However, others have become part of the domestic water supply system, such as the Rochdale Canal reservoirs at Blackstonedge and Chelburn, which now provide potable water to Manchester. In this way, canal reservoirs directly feed into modern drought preparedness.

Following restoration work undertaken by small groups of enthusiasts since the 1960s and 70s, British canals have experienced a renewal of interest and use. The impact and likelihood of water shortages on canals today is significantly reduced compared to during the industrial revolution, with canal water supplies centrally managed (since 2012 by the Canals and Rivers Trust) making competition between canal companies no longer an issue. Canal traffic is also more flexible and less critical, consisting mainly of leisure boaters, rather than providing deliveries essential for industry. Similar issues with balancing weather, demand and competition between water users, as faced by the canal companies at the turn of the nineteenth century, remain present today for other suppliers of water, such as water companies.

Although some of the water shortages discussed appear to have been a direct consequence of drought, it remains that the canal companies were ill prepared for extreme weather, and perhaps as the shortages in the 1790s demonstrate, even ill prepared for normal conditions in the face of changing water demands. Lack of preparedness for drought in the face of changing demand and expectations has been a concern across time, and one that remains relevant today (Taylor et al. 2009).

Conclusions

The development of new water supply solutions for the canal network, which following comparison of archival material and rainfall data appears to have been driven in part by responses to drought, was an important phase in the development of water supply systems in the Britain, which has been previously overlooked. Droughts had a serious impact on the early industrial canal network and were a source of anxiety for companies reliant on canal transport. By bringing together both instrumental and archival sources an enhanced understanding of the effects of dry weather on the canal network is beginning to emerge. The reconstructed composite precipitation series for Chatsworth House provides a valuable new long series for Central England. Droughts identified within the Chatsworth House series since 1800-present are not discussed here, but are comparable to those identified in other studies, such as 1870-72 (Todd et al. 2013); 1932-35 (Lennard et al. 2016); 1976 (Lennard et al. 2014) and 1996 (Spraggs et al. 2015). However, the wet period 1877-1883 is particularly notable, even compared to other long series. It is replicated and comparable in other local short series, suggesting that this period was particularly wet and worthy of further analysis. Water shortages linked to the dry weather and drought events in the 1780s and 1790s led to improvements in canal infrastructure, particularly through the development of larger reservoirs. The development of canal reservoirs preceded and informed the reservoirs developed in the nineteenth and twentieth centuries for drinking water, and pioneered systems of providing compensation water to rivers and streams.

Acknowledgments

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Figure Captions:

Fig. 1 Location of sites, topography and rainfall records used (Background map data from Digimap, ©Crown copyright and database rights 2019 Ordnance Survey (100025252))

Fig. 2 Chatsworth precipitation reconstruction A) annual average rainfall totals for three parts of the record prior to homogenisation; B) homogenised precipitation series. The thicker line represent 10-year moving average.

Fig. 3 Double mass curve of cumulative annual rainfall totals (top) for (a) Manchester and Chatsworth; (b) Spalding and Chatsworth; and (c) Manchester and Spalding; with corresponding test statistic (Tv) series (d,e,f) and ratio Qi series (g,h,i) performed following the SNHT approach of Alexandersson (1986). Grey lines in a, b, c indicate break points as shown in d, e, f. Chosen critical threshold level for Tv is 7.75, the 95 percent level, for n=25.

Fig. 4 Time series of dry and wet periods using SPI-6 (standardised precipitation index – using a six month series, top panel) and SPI-12 (standardised precipitation index – twelve month, bottom panel) reconstructions for Chatsworth, based on reconstructed precipitation series

Supporting Online Material Fig. 1 Register of rainfall published in the Memoirs of the Literary and Philosophical Society of Manchester (Garnett 1796)

Reference List

Archival Sources

ICE (Institution of Civil Engineers Archive) REN/RB/02/001 (1797) Rennie, Correspondence re. Rudyard Reservoir, dated 28th February 1797

SRO (Staffordshire Record Office) 6702/1 (1796-1803) Letter Book of Samuel Barnett and Company, Tin Plate Manufacturers of Kings Bromley

SRO D593/L/1/14/2 (1795) Letter from John Sparrow, Clerk of the Trent and Mersey Canal Company to Granville Leveson-Gower, 1st Marquess of Stafford, dated 7 September 1795

SRO D593/V/3/29 (1797) Minutes of the Lord's Committee to whom was referred the Bill, intituled, 'An Act to enable the Company of Proprietors of the Navigation from the Trent to the Mersey, to make a Navigable Canal from and out of the certain Branch of their said Navigation, called the Caldon Canal, at or near Endon, to or near the Town of Leek, in the County of Stafford; and also a Reservoir for suppling the several Canals of the said Company with Water' Ordered to be printed 14th March 1797

SRO D3186/1/1/1 (1766-1845) Minutes of half-yearly general meetings of the proprietors of the Staffordshire and Worcestershire Canal Company

SRO Q/SB 1810 T/466 (1810) Quarter Session Record (Highways and Bridges) Motion relating to indictment against inhabitants of Newcastle under Lyme for disrepair of highway July 1810

LLRRO 1785 (Leicestershire, Leicester and Rutland Record Office) DG39/1153 Letter from T. Potts, Bosworth to Francis Fortescue Turvile, Nancy, France. (TEMPEST database, https://www.nottingham.ac.uk/geography/extreme-weather/search/) Dated 25th July 1785

LLRRO 1785 DG39/708 Letter from John Eyston, Welford to Francis Fortescue Turvile (TEMPEST database) Dated 19th July 1785

TNA (The National Archive) RAIL 1019/15/41 (1797) The Case of the Manufacturers of the Staffordshire Potteries, Petitioners against the Caldon and Leek Canal and Reservoir Bill 10th January 1797

TNA RAIL 871/1 (1766-1785) Committee Order Book of the Staffordshire and Worcestershire Canal Company

TNA RAIL 871/2 (1803-1804) Committee Order Book of the Staffordshire and Worcestershire Canal Company

TNA RAIL 878 (1777-1853) Records of the Trent and Mersey Canal Company

Published Sources

Adamson, G.C.D., (2015) "Private Diaries as Information Sources in Climate Research." *Wiley Interdisciplinary Reviews: Climate Change* 6, no. 6: 599–611. doi: 10.1002/wcc.365.

Adamson, G.C.D., Hannaford, M.J., and Rohland, E.J., (2018) "Re-Thinking the Present: The Role of a Historical Focus in Climate Change Adaptation Research." *Global Environmental Change* 48: 195–205. doi: 10.1016/j.gloenvcha.2017.12.003.

Alexandersson, H. (1986). A homogeneity test applied to precipitation data. *J. Climatol.* **6**: 661–675. doi: 10.1002/joc.3370060607

Bazza, M. (2007). Overview of the history of water resources and irrigation management in the Near East region. *Water Sci. Technol. Water Supply* **7**: 201–209. doi: 10.2166/ws.2007.023

Binnie, G. M. (1987). *Early dam builders in Britain*, Thomas Telford Publishing. doi: 10.1680/edbib.03958.fm

Blair, J. ed. (2014). *Waterways and Canal-Building in Medieval England*, Oxford University Press, Oxford. doi: 10.1093/acprof:osobl/9780198723134.001.0001

Bond, J. (2014). Canal construction in the Early Middle Ages: an introductory review. In: *Waterways and Canal-Building in Medieval England*, Oxford University Press, Oxford: pp. 153–207. doi: 10.1093/acprof:osobl/9780198723134.003.0008

Boughey, J. and Hadfield, C. (1994). *Hadfield's British Canals: The inland waterways of Britain and Ireland*. 8th ed, Sutton, Stroud.

Brázdil, R., Dobrovoln, P., Trnka, M., Kotyza, O., Rezníčková, L., Valášek, H., Zahradníček, P. and Stěpánek, P. (2013). Droughts in the Czech Lands, 1090–2012 AD. *Clim Past* **9**: 1985–2002. doi: 10.5194/cp-9-1985-2013

Brázdil, R., Kiss, A., Luterbacher, J., Nash, D.J., Řezníčková, L., 2018. Documentary data and the study of past droughts: a global state of the art. Clim. Past 14, 1915–1960. doi: 10.5194/cp-14-1915-2018

Brázdil, R., Trnka, M., Dobrovolný, P., Chromá, K., Hlavinka, P. and Žalud, Z. (2008). Variability of droughts in the Czech Republic. *Theor. Appl. Climatol.* doi: 10.1007/s00704-008-0065-x

Brooks, J. and Glasspoole, C. E. P. (1928). *British Floods and Droughts*, Ernest Benn, London.

Camuffo, D., Bertolin, C., Diodato, N., Cocheo, C., Barriendos, M., Dominguez-Castro, F., Garnier, E., Alcoforado, M. J. and Nunes, M. F. (2013). Western Mediterranean precipitation over the last 300 years from instrumental observations. *Clim. Change* **117**: 85–101. doi: 10.1007/s10584-012-0539-9

Craddock, J. M. (1979). Methods of comparing annual rainfall records for climatic purposes. *Weather* **34**: 332–346. doi: 10.1002/j.1477-8696.1979.tb03465.x

Downward, S. and Skinner, K. (2005). Working rivers: the geomorphological legacy of English freshwater mills. *Area* **37**: 138–147. doi: 10.1111/j.1475-4762.2005.00616.x

Endfield, G. H., Tejedo, I. F. and O'Hara, S. L. (2004). Drought and disputes, deluge and dearth: climatic variability and human response in colonial Oaxaca, Mexico. *J. Hist. Geogr.* **30**: 249–276. doi: 10.1016/S0305-7488(03)00023-9

Farley, J. (1811). *General view of the agriculture and minerals of Derbyshire: with observations on the means of their improvement. Drawn up for the consideration of the Board of Agriculture and Internal Improvement.* Volume 1, Printed by B. McMillan, London.

Fink, A. H., Brücher, T., Krüger, A., Leckebusch, G. C., Pinto, J. G. and Ulbrich, U. (2004). The 2003 European summer heatwaves and drought -synoptic diagnosis and impacts. *Weather* **59**: 209–216. doi: 10.1256/wea.73.04

Freeman, M. J. (1980). Road transport in the English Industrial Revolution: An interim reassessment. *J. Hist. Geogr.* **6**: 17–28.

Gardiner, M. F. (2017). Inland Waterways and Coastal Transport: Landing Places, Canals and Bridges. In: *Water and the Environment in the Anglo-Saxon World*, Liverpool University Press, Liverpool, pp.152–166. doi: 10.2307/j.ctt1ps31q2

Garnett, T. (1796). *Meteorological Observations.* In: Memoirs of the Manchester Literary and Philosophical Society. **v4 part II**: pp. 517-640. https://www.biodiversitylibrary.org/item/52236

Garnier, E., Assimacopoulos, D. and van Lanen, H. A. J. (2015). *Drought-R&SPI Technical Report No.35: Historic Droughts beyond the modern instrumental records: an analysis of cases in United Kingdom, France, Rhine and Syros*, http://www.eu-drought.org/technicalreports

Groisman, P. Ya., Koknaeva, V.V., Belokrylova, T.A. and Karl, T.R. (1991) Overcoming biases of precipitation measurement: A history of the USSR experience, *Bulletin American Meteorological Society*, 72:1725-1733 doi: 10.1175/1520-0477(1991)072<1725:OBOPMA>2.0.CO;2

Hadfield, C. (1969). *The Canals of the West Midlands*, 2nd ed, David & Charles, Newton Abbot.

Hassan, J. A. (1985). The Growth and Impact of the British Water Industry in the Nineteenth Century. *Econ. Hist. Rev.* 531. doi: 10.1111/j.1468-0289.1985.tb00387.x

Jankovic, V. (2000). *Reading the Skies: A Cultural History of English Weather, 1650-1820*, Manchester University Press, Manchester.

Jones, P. D. and Lister, D. H. (1998). Riverflow reconstructions for 15 catchments over England and Wales and an assessment of hydrologic drought since 1865. *Int. J. Climatol.* **18**: 999–1013. doi: 10.1002/(SICI)1097-0088(199807)18:9<999::AID-JOC300>3.0.CO;2-8

Jones, C. A., Davies, S. J., and Macdonald. N. (2012) “Examining the Social Consequences of Extreme Weather: The Outcomes of the 1946/1947 Winter in Upland Wales, UK.” *Climatic Change* 113, no. 1 35–53. doi: 10.1007/s10584-012-0413-9.

Van Lanen, H. A. J. (2006). Drought propagation through the hydrological cycle. *Climate Variability and. Change- Hydrological Impacts* (Proceedings of the Fifth FRIEND World Conference held at Havana, Cuba, November 2006), IAHS Publ. **308**: 122–127.

Lennard, A. T., Macdonald, N., Clark, S. and Hooke, J. M. (2015). The application of a drought reconstruction in water resource management. *Hydrol. Res.***47 (3):** 646-659 doi: 10.2166/nh.2015.090

Lennard, A. T., Macdonald, N. and Hooke, J. M. (2014). Analysis of drought characteristics for improved understanding of a water resource system. *Evolving Water Resources Systems: Understanding, Predicting and Managing Water–Society Interactions* (Proceedings of ICWRS2014, Bologna, Italy, June 2014) IAHS Publ. **364**: 404–409.

Van Lieshout, C. (2016). Droughts and Dragons: Geography, Rainfall, and Eighteenth-Century London’s Water Systems. *Technol. Cult.* **57**: 780–80559. doi: 10.1353/tech.2016.0107

Lindsay, J. (1979). *The Trent and Mersey Canal*, David & Charles, Newton Abbot.

Van Loon, A. F., Gleeson, T., Clark, J., Van Dijk, A. I. J. M., Stahl, K., Hannaford, J., Di Baldassarre, G., Teuling, A. J., Tallaksen, L. M., Uijlenhoet, R., Hannah, D. M., Sheffield, J., Svoboda, M., Verbeiren, B., Wagener, T., Rangecroft, S., Wanders, N. and Van Lanen, H. A. J. (2016a). Drought in the Anthropocene. *Nat. Geosci.* **9**: 89–91. doi: 10.1038/ngeo2646

Van Loon, A. F., Stahl, K., Di Baldassarre, G., Clark, J., Rangecroft, S., Wanders, N., Gleeson, T., Van Dijk, A. I. J. M., Tallaksen, L. M., Hannaford, J., Uijlenhoet, R., Teuling, A. J., Hannah, D. M., Sheffield, J., Svoboda, M., Verbeiren, B., Wagener, T. and Van Lanen, H. A. J. (2016b). Drought in a human-modified world: Reframing drought definitions, understanding, and analysis approaches. *Hydrol. Earth Syst. Sci.* **20**: 3631–3650. doi: 10.5194/hess-20-3631-2016

Macdonald, N. and Sangster, H. (2017). High-magnitude flooding across Britain since AD 1750. *Hydrol. Earth Syst. Sci.* **21**: 1631–1650. doi: 10.5194/hess-21-1631-2017

Manley, G. (1972). Manchester rainfall since 1765. *Memoirs of the Manchester Literary and Philosophical Society* **114**: 70-89

Marsh, T., Cole, G. A. and Wilby, R. (2007). Major droughts in England and Wales, 1800 - 2006. *Weather* **62**: 87–93. doi: 10.1002/wea.67

Marsh, T. J., Greenfield, B. J. and Hannaford, J. (2005). The 1894 Thames flood - A reappraisal. *Proc. Inst. Civ. Eng. Water Manag.* **158**: 103–110. doi: 10.1680/wama.2005.158.3.103

Mckee, T. B., Doesken, N. J. and Kleist, J. (1993). The relationship of drought frequency and duration to time scales. *AMS 8th Conf. Appl. Climatol.* 179–184.

Met Office (2018). Met Office MIDAS Open: UK Land Surface Stations Data (1853-current). Centre for Environmental Data Analysis, *Jan 2018*.

Mitchell, J.K. (2011) “Looking Backward to See Forward: Historical Changes of Public Knowledge about Climate Hazards in Ireland.” *Irish Geography* 44, no. 1: 7–26. doi: 10.1080/00750778.2011.615492.

Morgan, J. E. (2016). The representation and experience of English urban fire disasters, c. 1580-1640. *Hist. Res.* **89**: 268–293. doi: 10.1111/1468-2281.12123

Mukerji, C. (2009). *Impossible Engineering: Technology and Territoriality on the Canal du Midi*, Princeton University Press, Princeton and Oxford.

Namias, J. (1981). Severe Drought and Recent History. In: *Climate and History: Studies in Interdisciplinary History*, Princeton University Press, Princeton (U.S.) Guildford (U.K.), pp.117–132. *JSTOR*, www.jstor.org/stable/j.ctt7zv859.9.

Olivier-Smith, A. and Hoffman, S. (1999). A Cultural and Social Construction of Catastrophe. In: *The Angry Earth: Disaster in Anthropological Perspective*, Routledge, London, pp.73–88.

Groisman, P. Ya., V. V. Koknaeva, T. A. Belokrylova and T. R. Karl (1991). Overcoming Biases of Precipitation Measurement: A History of the USSR Experience. *Bull. Am. Meteorol. Soc.* 1725-1733 doi: 10.1175/1520-0477(1991)072<1725:OBOPMA>2.0.CO;2

Pedgley, D. E. (2002). A short history of the British Rainfall Organization. Occasional Papers on Meteorological History No. 5. Royal Meteorological Society

Plymley, J. (1803). *General View of the Agriculture of Shropshire: with observations. Drawn up for the consideration of the Board of Agricultural and Internal Improvement* Printed by B. McMillan, London.

Porter, E. (1978). *Water management in England and Wales.* Cambridge : Cambridge University Press, 1978.

Rhodes, E. (2014). Identifying Human Modification of River Channels. *Waterways and Canal-Building in Medieval England*, Oxford University Press, Oxford, pp.133–153. doi: 10.1093/acprof:osobl/9780198723134.003.0007

Rodda, J. C. and Marsh, T. J. (2011). *The 1975-76 Drought-a contemporary and retrospective review*, Centre for Ecology & Hydrology Wallingford.

Sangster, Heather, Jones, C., and Macdonald, N. (2018) “The Co-Evolution of Historical Source Materials in the Geophysical, Hydrological and Meteorological Sciences: Learning from the Past and Moving Forward.” *Progress in Physical Geography* 42, no. 1: 61–82. doi: 10.1177/0309133317744738

Satchell, M. (2017). Navigable waterways and the economy of England and Wales: 1600-1835. *The Online Atlas of Transport, Urbanization and Economic Development c. 1680-1911*, Cambridge.

Spinoni, J., Naumann, G., Vogt, J. V. and Barbosa, P. (2015). The biggest drought events in Europe from 1950 to 2012. *J. Hydrol. Reg. Stud.* **3**: 509–524. doi: 10.1016/j.ejrh.2015.01.001

Spraggs, G., Peaver, L., Jones, P. and Ede, P. (2015). Re-construction of historic drought in the Anglian Region (UK) over the period 1798-2010 and the implications for water resources and drought management. *J. Hydrol.* **526**: 231–252. doi: 10.1016/j.jhydrol.2015.01.015

Stone, D. (2014). The impact of drought in early fourteenth-century England. *Econ. Hist. Rev.* **67**: 435–462. doi: 10.1111/1468-0289.12035

Strauss, S. and Orlove, B. S. (2003). *Weather, climate, culture*, Berg, Oxford.

Taylor, V., Chappells, H., Medd, W. and Trentmann, F. (2009). Drought is normal: the socio-technical evolution of drought and water demand in England and Wales, 1893–2006. *J. Hist. Geogr.* **35**: 568–591. doi: 10.1016/j.jhg.2008.09.004

Todd, B., Macdonald, N., Chiverrell, R. C., Caminade, C. and Hooke, J. M. (2013). Severity, duration and frequency of drought in SE England from 1697 to 2011. *Clim. Change* **121**: 673–687. doi: 10.1007/s10584-013-0970-6

Veale, L., Endfield, G. H., Davies, S., Macdonald, N., Naylor, S., Royer, M.-J., Bowen, J., Tyler-Jones, R. and Jones, C. (2017). Dealing with the deluge of historical weather data: the example of the TEMPEST database. *Geo Geography and Environment* **4**: e00039 doi: 10.1002/geo2.39

Waddington, K. (2017). “I should have thought that Wales was a wet part of the world”: Drought, rural communities and public health, 1870-1914. *Soc. Hist. Med.* **30**: 590–611. doi: 10.1093/shm/hkw118

Westermann, A, and Rohr, C. (2015) “Climate and beyond : The Production of Knowledge about the Earth as a Signpost of Social Change ; an Introduction.” *Historical Social Research* 40, no. 2: 7–21. doi: 10.12759/hsr.40.2015.2.7-21

Wetter, O., Pfister, C., Werner, J. P., Zorita, E., Wagner, S., Seneviratne, S. I., Herget, J., Grünewald, U., Luterbacher, J., Alcoforado, M.-J., Barriendos, M., Bieber, U., Brázdil, R., Burmeister, K. H., Camenisch, C., Contino, A., Dobrovolný, P., Glaser, R., Himmelsbach, I., Kiss, A., Kotyza, O., Labbé, T., Limanówka, D., Litzenburger, L., Nordl, Ø., Pribyl, K., Retsö, D., Riemann, D., Rohr, C., Siegfried, W., Söderberg, J. and Spring, J.-L. (2014). The year-long unprecedented European heat and drought of 1540 – a worst case. *Clim. Change* **125**: 349–363. doi: 10.1007/s10584-014-1184-2

Wilhite, D. A. and Glantz, M. H. (1985). Understanding the Drought Phenomenon: The Role of Definitions, *Water International*, **10 (3):** 111-120 doi: 10.1080/02508068508686328

Zaidman, M. D., Rees, H. G. and Young, A. R. (2002). Spatio-temporal development of streamflow droughts in north-west Europe. *Hydrol. Earth Syst. Sci.* **6**: 733–751. doi: 10.5194/hess-6-733-2002

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RE: REEC-D-18-00678

16 May 2019

Dear Dr Reyer,

We are pleased to resubmit for publication manuscript REEC-D-18-00678 "*Dry Weather Fears of Britain's Early 'Industrial' Canal Network*" following minor revisions. Please find below a table containing responses to the reviewer and editor's comments and changes made.

Yours sincerely

Alice Harvey-Fishenden

On behalf of, Drs Neil Macdonald and James Bowen

1) Please go once more through the manuscript and tighten the text and make it short and concise wherever possible.	The manuscript has been proof read for typos and inconsistencies, and edited for brevity and clarity.
2) Figure 2: Please use lower case "(a)" and "(b)" for designating the current panels A and B to avoid confusion with the "A", "B" and "C" that are part of panel A and to be consistent with the subpanel designation in Figure 3.	Done.
3) Figure 3: explain in the caption what the vertical grey lines mean in panels a,b,c,==>pointing towards special years in d,e,f, and also explain what the horizontal grey line in panels b,e,f, means	Figure 3 caption revised accordingly.
4) Figure 4: Explain what SPI-6 and SPI-12 mean and the caption should explain what the figure is about, in your case sth like: "Time series of dry and wet periods using SPI-6 (standardised precipitation index – using a six month series, top panel) and SPI-12 (standardised precipitation index – twelve month, bottom panel) reconstructions for Chatsworth, based on reconstructed precipitation series."	Caption has been revised as suggested.
5) Online figure 5 should be "Supporting Online Material Figure 1", also in the text.	This has been changed in the text and in the figure captions.
SI Editor: Many thanks for the submission of the revised paper. I agree with the reviewer, that it improved considerably but the manuscript still needs minor revisions. Please follow the instructions given by the reviewer. In addition, I think there is something odd with the sentence on p. 6, line 116 and 117.	A full stop and (missing) capital letter have been added.
Reviewer #1: I am happy with all the revisions done, as specified in the authors' response. However, prior to final acceptance, I would recommend careful editing of the manuscript. The manuscript still contains a lot of inconsistencies in its current form. For example, the abstract states that "dry weather… reconstructed from a combination of narrative and instrumental sources." As far as I understood, only instrumental records have been used to reconstruct the precipitation time-series, whereas narrative sources have	The manuscript has been proof read for typos and inconsistencies, and edited for brevity and clarity. I have removed 'combination of narrative and' from the abstract to avoid confusion.

been used to study the societal impacts of drought.	
Moreover, the manuscript still includes several typos, for example with the use of brackets (see, e.g. page 2: lines 6, 10, 11, and further). One specific note: it should not be as "documented by (Marsh et al. 2007)" but as "documented by Marsh et al. (2007)". This same issue appears also later in the manuscript.	All references have been checked for errors.
Also, the authors should be more consistent with the vocabulary. Now, for example in Table 1, both "monthly and annual data" and "monthly and annual totals" are used. If one series are referred in the table as "totals" but the other is not, the reader is puzzled what the "data" is. Totals, means or something else? Now this information can be found in the body text, but I would strongly advice being consistent with the vocabulary, throughout the manuscript and including all the figures and tables.	Table 1 has been revised accordingly.
Furthermore, I would suggest the authors submitting the figures as scalable vector graphs (instead of raster images). This would improve the quality of the figures (e.g. fig. 3 where the text is still difficult to read).	We are very happy to supply Fig 3 as a scalable vector graph and have tried to do so, however the online submission system will only allow us to upload it as 'Electronic Supplementary Material' in this format. We have therefore left it as a .tif file. Please let us know if you would like the .svg file.
Please, note that the issues mentioned above are just couple remarks, and the manuscript includes other minor inconsistencies and errors. Nonetheless, I think that the manuscript has greatly improved from its earlier state and am happy to recommend it for publication after careful editing.	The manuscript has been proof read for typos and inconsistencies, and edited for brevity and clarity.

Figure 1

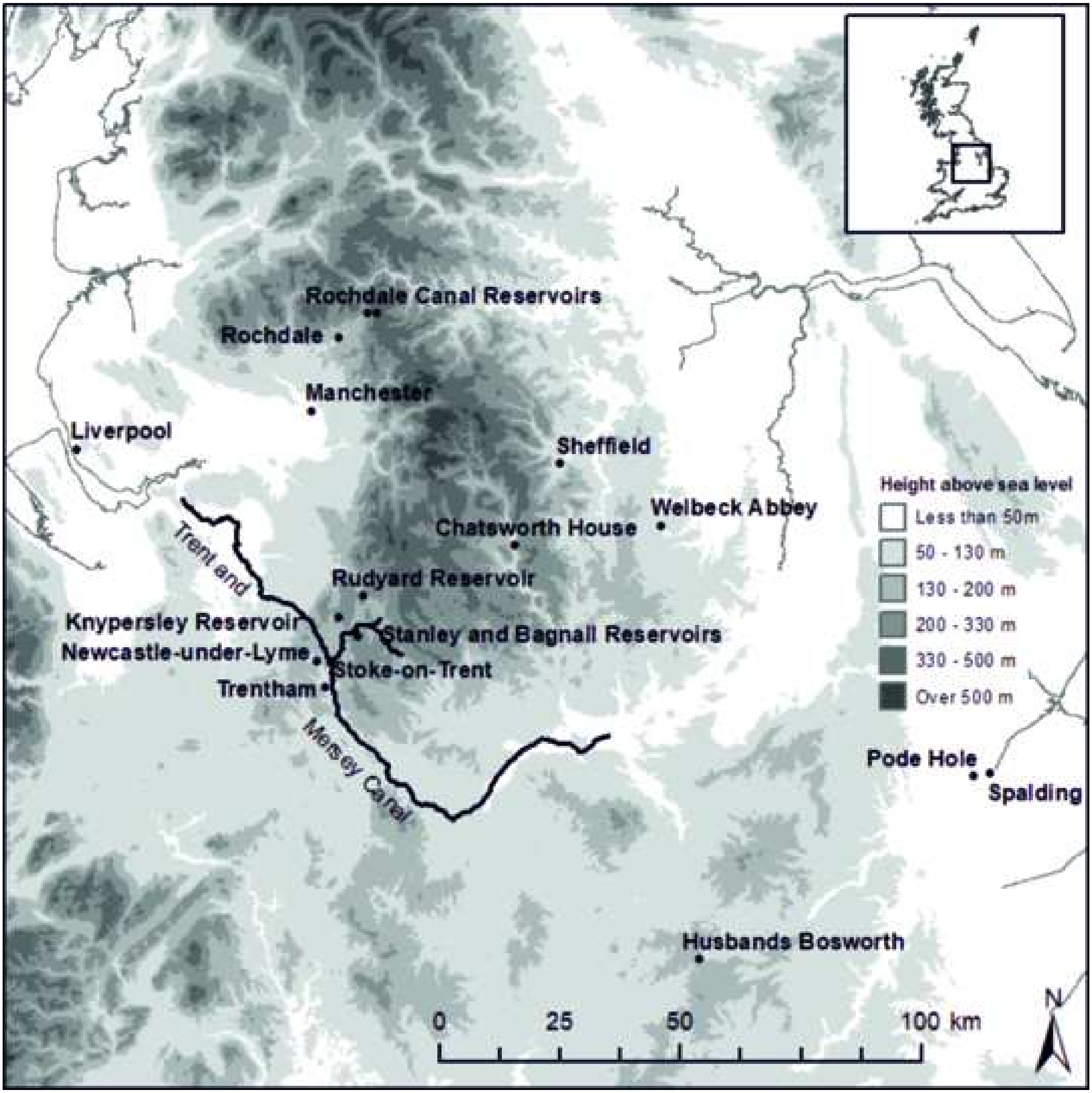
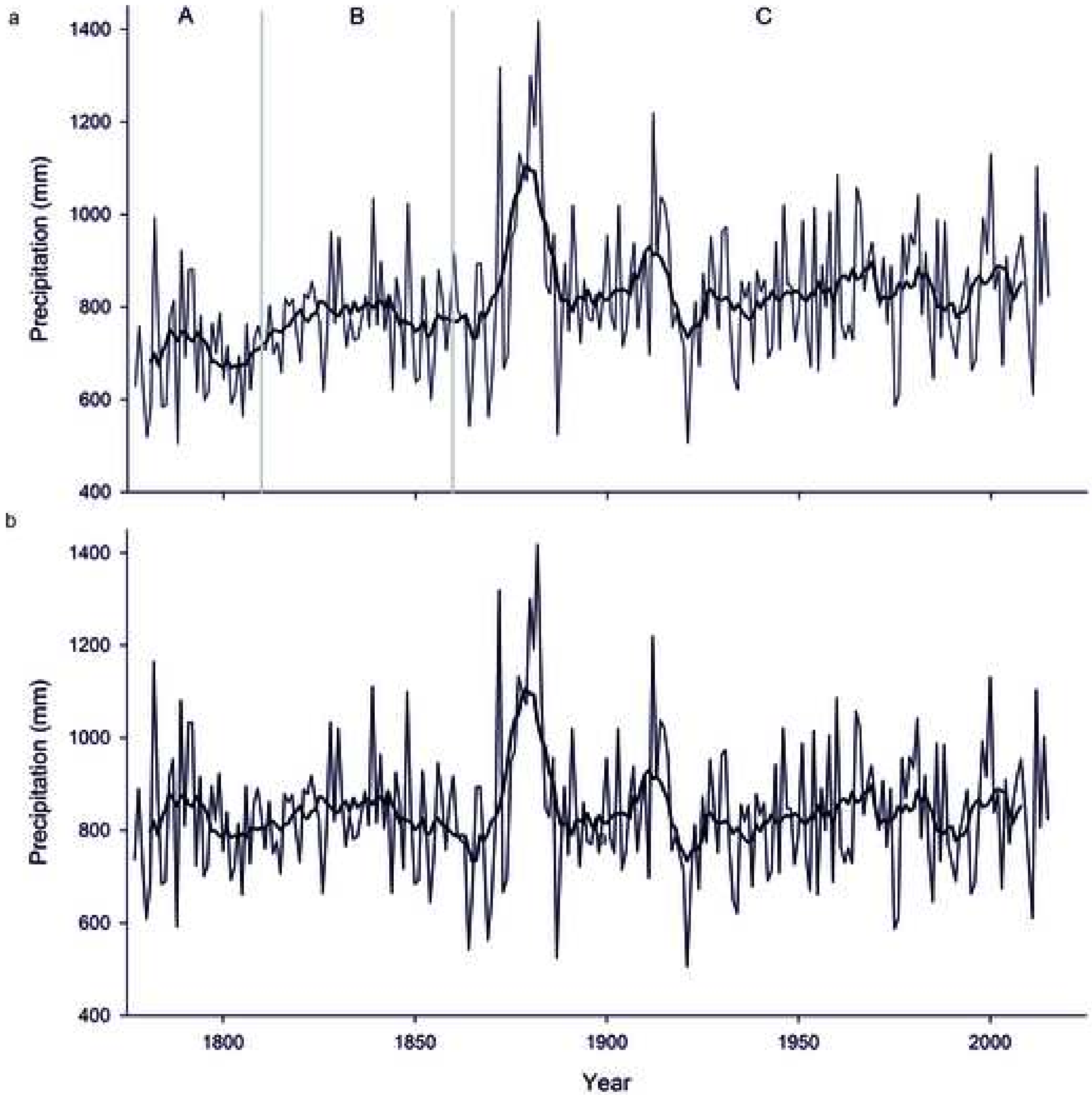

Rochdale Canal Reservoirs
Rochdale
Manchester
Liverpool
Sheffield
Welbeck Abbey
Chatsworth House
Trent and
Rudyard Reservoir
Knypersley Reservoir
Stanley and Bagnall Reservoirs
Newcastle-under-Lyme
Stoke-on-Trent
Trentham
Mersey Canal
Height above sea level
Less than 50m
50 - 130 m
130 - 200 m
200 - 330 m
330 - 500 m
Over 500 m
Pode Hole
Spalding
Husbands Bosworth
0
25
50
100 km
N

Figure 2



a
A
B
C
1400
1200
1000
800
600
400
Precipitation (mm)
b
1400
1200
1000
800
600
400
Precipitation (mm)
1800
1850
1900
1950
2000
Year

Figure 3

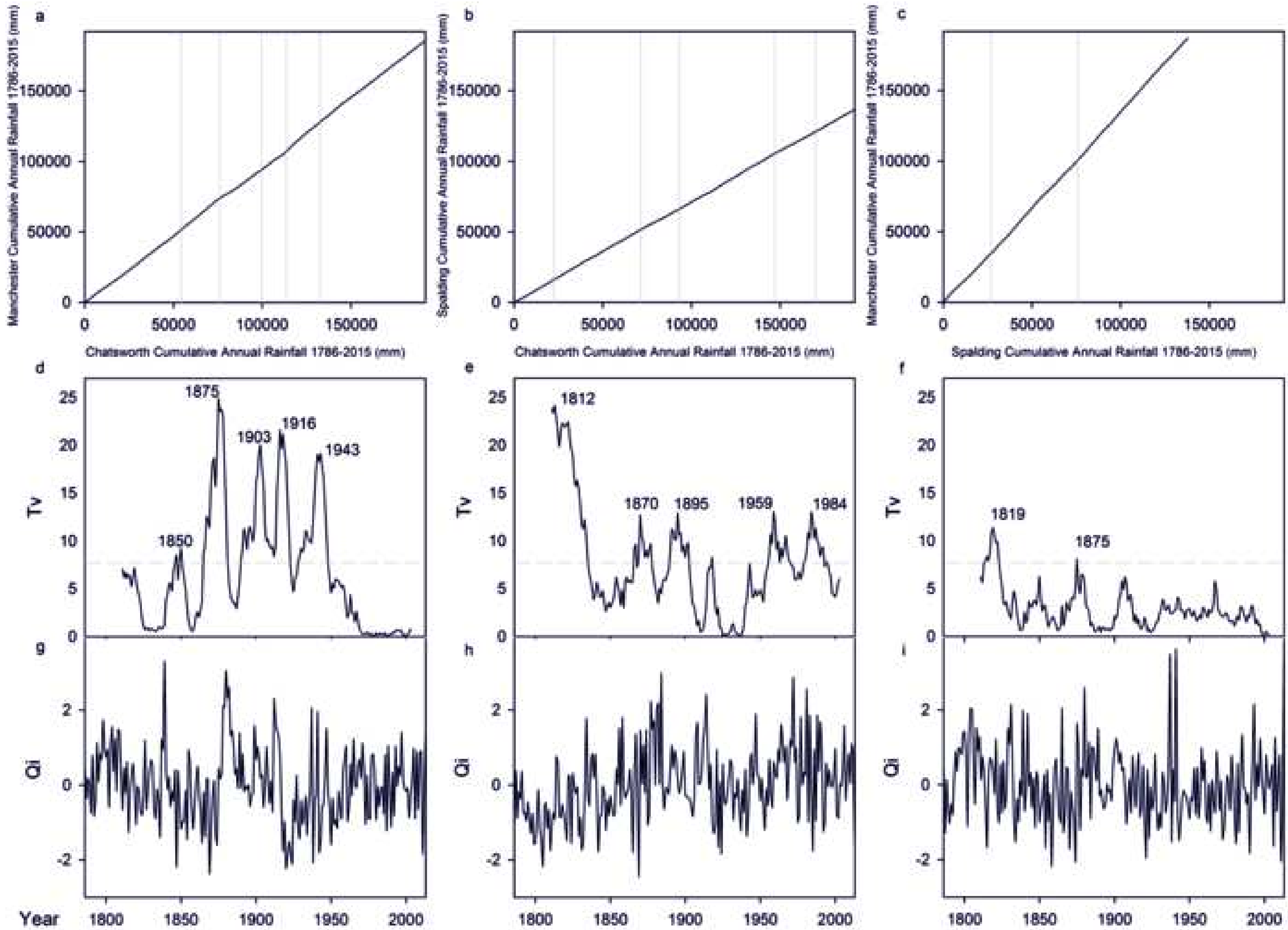
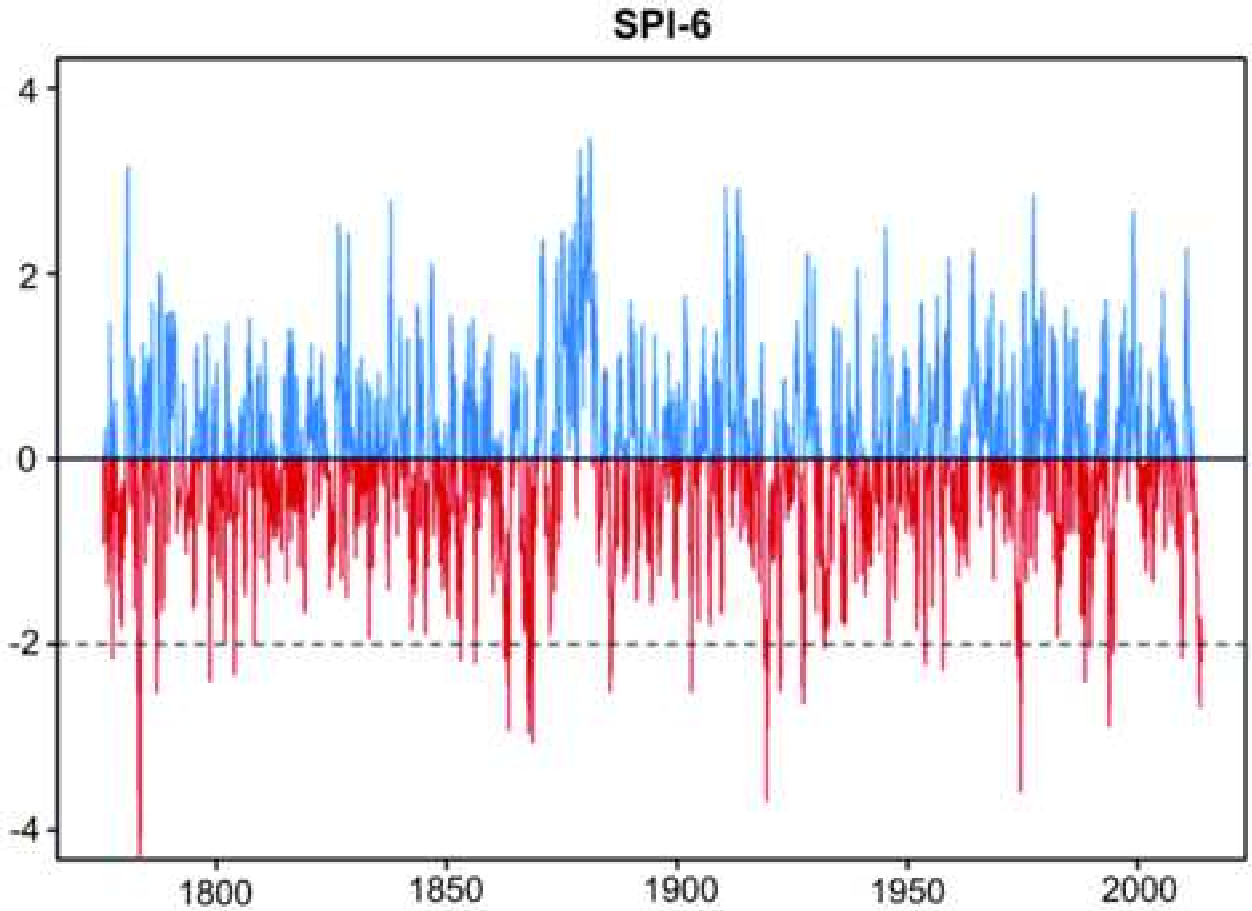

a
b
c
Manchester Cumulative Annual Rainfall 1786-2015 (mm)
Spalding Cumulative Annual Rainfall 1786-2015 (mm)
Chatsworth Cumulative Annual Rainfall 1786-2015 (mm)
Spalding Cumulative Annual Rainfall 1786-2015 (mm)
0
50000
100000
150000
d
e
f
Tv
1875
1903
1916
1943
1850
1812
1870
1895
1959
1984
1819
0
5
10
15
20
25
g
h
i
Qi
-2
2
Year
1800
1850
1900
1950
2000

Figure 4


SPI-6
4
2
0
-2
-4
1800
1850
1900
1950
2000

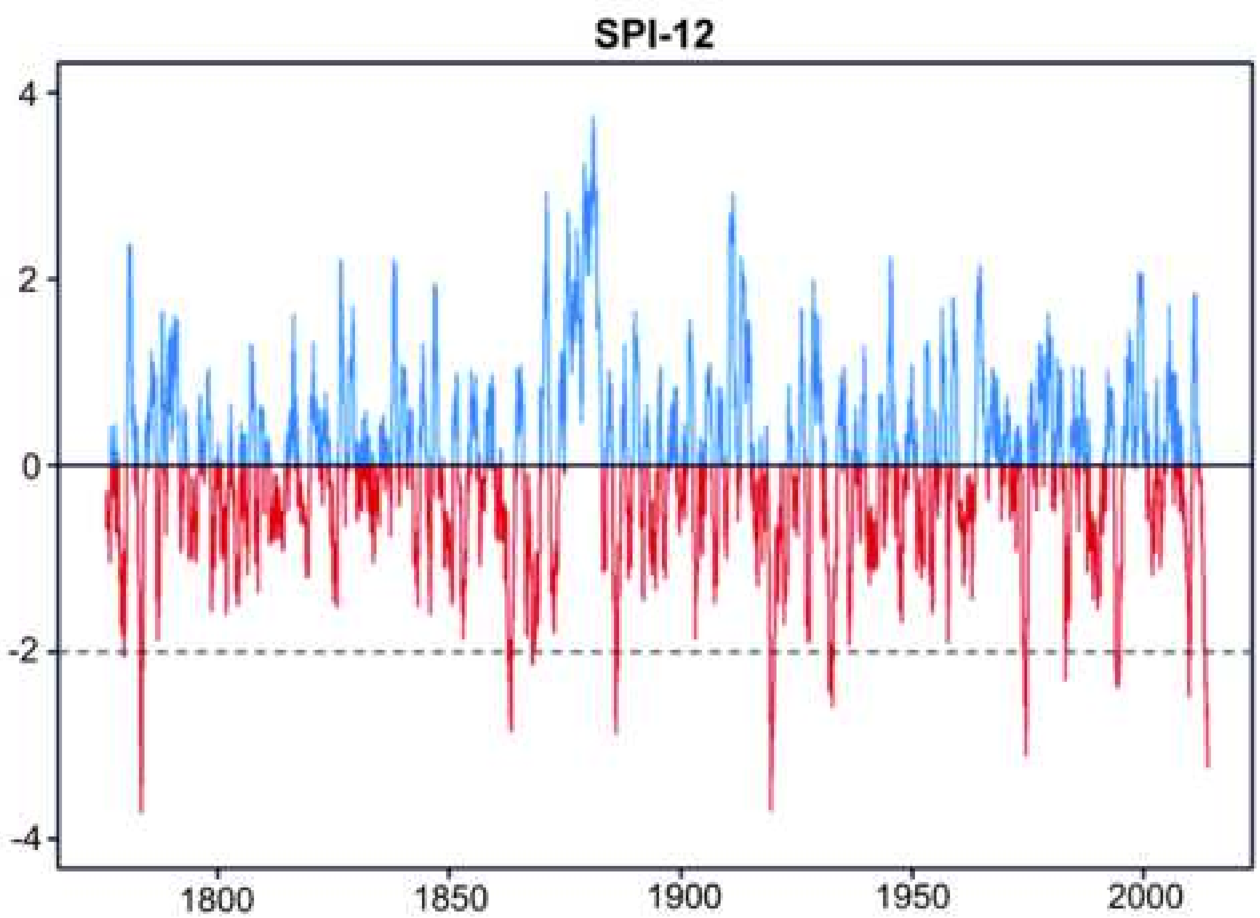

SPI-12
4
2
0
-2
-4
1800
1850
1900
1950
2000

Table 1 Sources of data for the reconstruction of the Chatsworth rainfall series.

Station	Date	Source	Observer	Notes
Chatsworth	1760-9	Met office ten year books	-	Annual totals only
Chatsworth	1761-1810	Farey,		Annual totals, some monthly values quoted in the text.
Chatsworth	1777-93	Met office ten year books. Data extracted from the Memoirs of the Literary and Philosophical Society Manchester (Garnett, 1793)	Lord George Cavendish	Monthly and annual totals
Chatsworth	1794-9	Met office ten year books	Lord George Cavendish	Annual totals only
Chatsworth	1800-13	Met office ten year books	-	Monthly and annual totals
Wellbeck Abbey	1806-1878	Met office ten year books		Monthly and annual totals
Chatsworth Gardens	1860-9	Met office ten year books		Monthly and annual totals. Jan-Mar 1860 missing and no annual total for 1860
Chatsworth	1861-1956	Chatsworth register of Rainfall, House archive		Monthly and annual totals
Chatsworth Gardens	1861-current	BADC: digitised from 1878		Station ID 544, missing data includes: 1882, 1883,1884, 1886, 1924, Mar-Dec 1976, Jun 1984, Sep 1984, Jan 1985, Feb 1988, Dec 1997, Aug 2001, Jan, Feb 2002, Aug-Dec 2002, Sep 2005, Nov-Dec 2012. Single missing months in-filled with interpolation. Pre-1925 years filled with digitised archive photographs. More recent missing months in-filled via linear regression with BADC station 552.